This document was prepared in conjunction with work accomplished under Contract No. DE-AC09-96SR18500 with the U.S. Department of Energy.

Wireless For A Nuclear Facility

Davis Shull and Joseph Cordaro, Savannah River National Laboratory, Aiken, SC

ABSTRACT

The introduction of wireless technology into a government site where nuclear material is processed and stored brings new meaning to the term "harsh environment". At SRNL, we are attempting to address not only the harsh RF and harsh physical environment common to industrial facilities, but also the "harsh" regulatory environment necessitated by the nature of the business at our site. We will discuss our concepts, processes, and expected outcomes in our attempts to surmount the roadblocks and reap the benefits of wireless in our "factory".

BACKGROUND

The Department of Energy (DOE) is responsible for the stewardship of the U.S.'s nuclear weapons program, from maintaining a strong nuclear deterrent to environmental cleanup and decommissioning of legacy nuclear materials and facilities in the Nuclear Weapons Complex (NWC). The National Nuclear Security Agency (NNSA), which is part of the Department of Energy, manages the U.S. nuclear stockpile. The NNSA's nuclear weapons complex consists of the eight major facilities across the country. The facilities include: Los Alamos National Laboratory (NM), Lawrence Livermore National Laboratory (CA), Sandia National Laboratories (NM and CA), Pantex Plant (TX), Y-12 National Security Complex (TN), Kansas City Plant (MO), Savannah River Site (SC) and the Nevada Test Site (NV).

In this paper we will present the challenges to implementing wireless technology at the Savannah River Site and other NWC locations and our concepts and processes aimed at addressing these challenges. We will also discuss a current wireless technology project at our site, our implementation path, and expected outcome.

PHYSICAL ENVIRONMENT

Like many other "industrial" environments, the facilities of the NWC present many environmental and physical impediments to the use of wireless technologies. Most of the physical structures in the plant processing areas are constructed of thick concrete, rebar, and stainless steel components. Many contain large stainless steel tanks, glove box containment systems, piping, valves, pumps, motors, fans, and ventilation ductwork. All of these types of structural materials and process equipment tend to create highly reverberant RF environments rich with opportunities for multi-path interference.

Wireless devices would also be subjected to many sources of electromagnetic interference in the NWC facilities. In addition to the interfering electromagnetic emissions of various motor and motor drive systems, several different types of welding processes are also commonly used in many of the plant areas. Process controllers, computing equipment, and handheld communications radios are also potential sources of EMI that could hinder successful wireless technology deployments.

Besides the rather harsh RF environment present, potential RF devices must co-exist with other legacy wired process instruments and equipment, as well as any other previously installed RF equipment. Many of the process areas contain very sensitive instrumentation such as airborne radioactive contamination monitors, nuclear criticality monitors, and personnel contamination monitors. Other security, communications, and process controls equipment must also remain “unharmed” by any proposed RF technology equipment.

The physical environment of the NWC processing facilities may also present challenges of extreme temperatures, humidity, varying levels of pressure and vacuum, and corrosive vapors from many of the chemicals in use and in storage. Some applications would also subject the wireless device to vibration and dynamic shock. Perhaps the most challenging environmental factor influencing the deployment of wireless sensor technologies in the NWC, however, is the ionizing radiation level present in many of the processing facilities. Special consideration must be given to any electronics and materials that will be subjected to large cumulative doses of gamma radiation that can easily reach 10^6 rad (for perspective, note that the lethal acute dose for humans is approximately 600 rad[1]). Implementation options for RF technology in these radiological environments consist of the use of rad-hardened devices able to withstand larger doses of radiation before failure, incorporating appropriate radiation shielding to protect the sensitive components without rendering the RF communications ineffective, locating the sensitive parts of the design as far away from the higher dose areas as possible, or most likely, some combination of all of the above.

Other foundational technical issues that must be addressed in any proposed wireless technology deployments are reliability, throughput, latency, and security. The physical sensor quality must also not be overlooked. Wireless solutions may not be viewed as favorable options if they require a sacrifice of sensor quality as compared with wired systems.

REGULATORY ENVIRONMENT

Because of the nature of the work performed at the NWC sites and the corresponding security emphasis, wireless devices are subject to restrictions regarding their operation and location. Proposed wireless deployments must pass a lengthy approval process and possess the appropriate level of documentation prior to installation in a facility. Early communication and involvement with the reviewing and approving parties will help to avoid delays and ensure a successful deployment. As the number of successful wireless deployments across the NWC increases, new projects can hopefully build from previous successes through the use of similar approved plans and documentation as templates and by taking advantage of lessons learned from these previous deployments. A wireless technology approval process involves some or all of the following depending on the details and components of the wireless system. Each NWC site’s process may vary slightly depending on the interpretation of requirements, site implementing procedures, and the level of acceptable risk as determined by that site’s Designated Approval Authority.

Spectrum Supportability Authorization: An assessment must be performed by the local frequency coordinator to determine whether the electromagnetic spectrum is available or will be available over the expected life cycle of the RF system. For federal government use, the National Telecommunications and Information Administration (NTIA) regulates spectrum management. The NTIA regulations, DOE requirements, and the specific NWC site's local contractor's procedures will direct the use of spectrum-dependent equipment.

Procurement Authorization: An additional approval by the local frequency coordinator is required for all purchases of RF transmitting devices. Additional procurement regulations may give preference to specific suppliers or require additional justification for purchasing from other suppliers.

Risk Assessment: A risk assessment must be prepared for all wireless technology deployments to evaluate the risks to computing assets. The risk assessment will identify the risks, analyze the risks for impact, develop mitigation and handling strategies, and determine any remaining risk after mitigation. Mitigation strategies may need to be layered in order to achieve a level of residual risk that is acceptable.

Security Plan: A security plan is required to address specific restrictions in location and operation of wireless technologies at each NWC site. The security requirements and necessary controls will vary depending on the type and level of the security area and the sensitivity of the data processed or transmitted by the system. Controls will most likely be a layered combination of physical, technical, personnel, and administrative controls. Security approvals can involve many different site contractor organizations, disciplines, and potentially multiple DOE organizations at each NWC site (ex.: NNSA and Environmental Management (EM)). Early involvement with these parties is key to a successful wireless technology deployment. Approvals may also get elevated to DOE Headquarters depending on the specific aspects of the deployment.

Test Plan: Testing must be performed to verify that all design goals were met and to assure that the requirements of the security plan are met. These tests should be performed prior to the introduction of any sensitive process measurements or data to the system.

POTENTIAL BENEFITS AND APPLICATIONS

WIRELESS SENSOR NETWORKS

The majority of radioactive material processing in the facilities of the NWC is performed in containment glove boxes or radioactively "hot" work cells. Glove boxes can be single standalone enclosures with one or two glove port working locations, or can extend to multi-room enclosures that have numerous glove port working locations, possibly extending vertically to multiple working heights or platforms. These glove boxes are generally constructed of stainless steel with single or multi-layered glass windows and are commonly maintained at some level of negative pressure to ensure containment. Electrical cables and mechanical piping must enter and exit these glove boxes at built-in penetrations that maintain the glove box confinement. Similarly, hot work cells may have speciallydesigned cable conduit penetrations that maintain cell confinement and also provide radiation shielding by incorporating various turns and bends in the conduit path.

The need for additional glove box penetrations or work cell cable conductors is a common problem as existing facilities in the NWC continue to be upgraded or modified to meet emerging needs or future missions and new sensor signal capacities are created. Design upgrades of this type can be especially costly as many of these containment systems are seismically qualified designs and provide key safety protection for the workers. Simply adding a few more sensors inside a containment environment can result in the need for additional cables, conduits or cable trays, containment penetrations, cable connectors, termination points, and termination cabinets in already crowded existing facilities. Material costs for these modifications are also significant as many of the cables and connectors are specialty-type items designed for the nuclear processing environment. In order to achieve these modifications, work must be performed in radioactively contaminated areas at great expense and increased hazardous exposure to the worker. Installation costs are also drastically impacted by the additional quality control inspections, work planning/control, and project approvals required by modifications to these types of systems and structures, especially when a breach of containment is required.

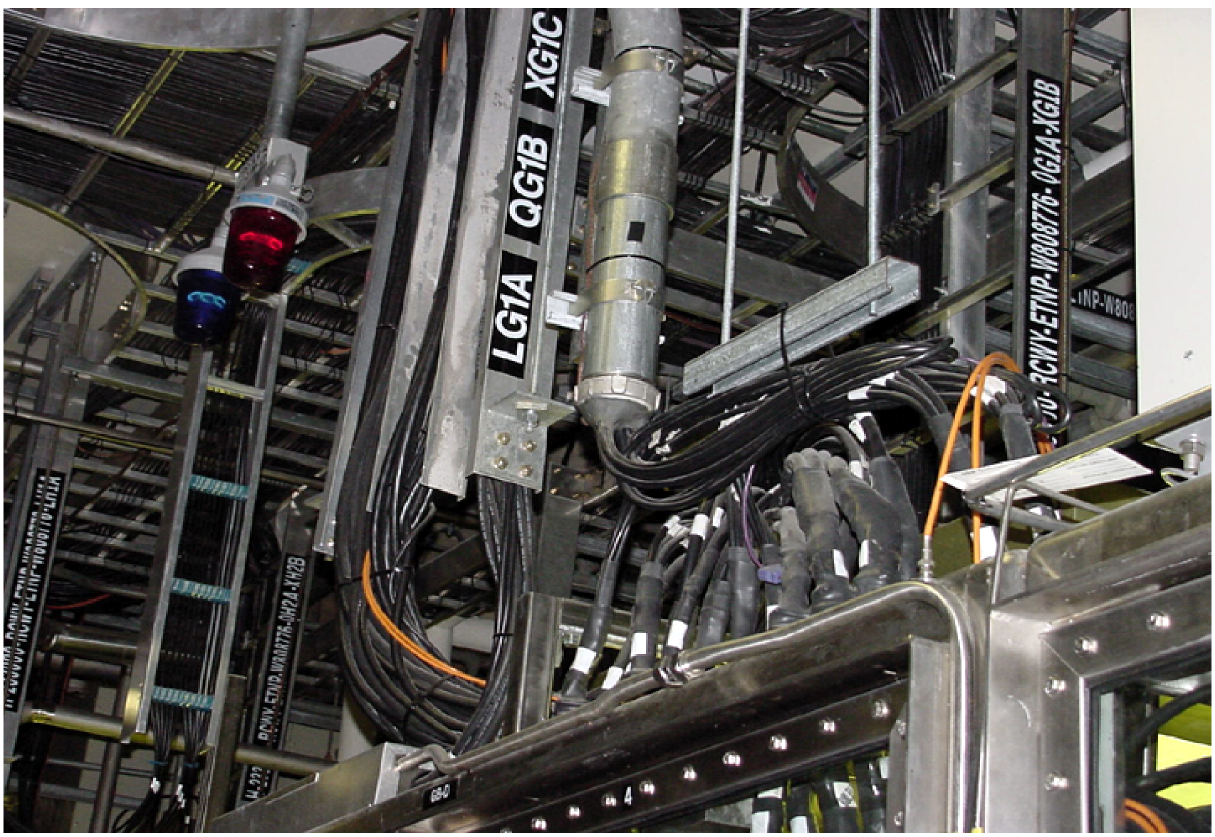

Figure 1: Typical Glove Box Wiring at the Savannah River Site

The use of short-range wireless sensor networks in these glove box and hot work cell environments has the potential to save millions of dollars in design and installation costs by providing an alternative means for signal transmission out of the containment environment. Material costs would also be reduced as thousands of feet of cable, penetrations, connectors, conduit, etc. are eliminated. By simplifying these facility modifications through the elimination of these items and minimizing the physical modifications to the containment systems, worker hazardous exposure (both radiological and non-radiological industrial) can be greatly reduced. The use of wireless devices will greatly reduce the amount of contaminated waste that is generated during installation and also at the end of system life when it is dismantled and disposed. Further longer-term cost savings may also be achieved through the reduction of maintenance associated with cable repair and connection rework during the lifetime of the system.

Likewise, in the case of new facilities, a designer is faced with the difficult task of signal cable management, where space is at a premium and requirements for additional cables seem to be a daily occurrence. The use of wireless sensor networks in new facility designs could also reduce design, installation, and material costs, while helping to conserve valuable facility real-estate.

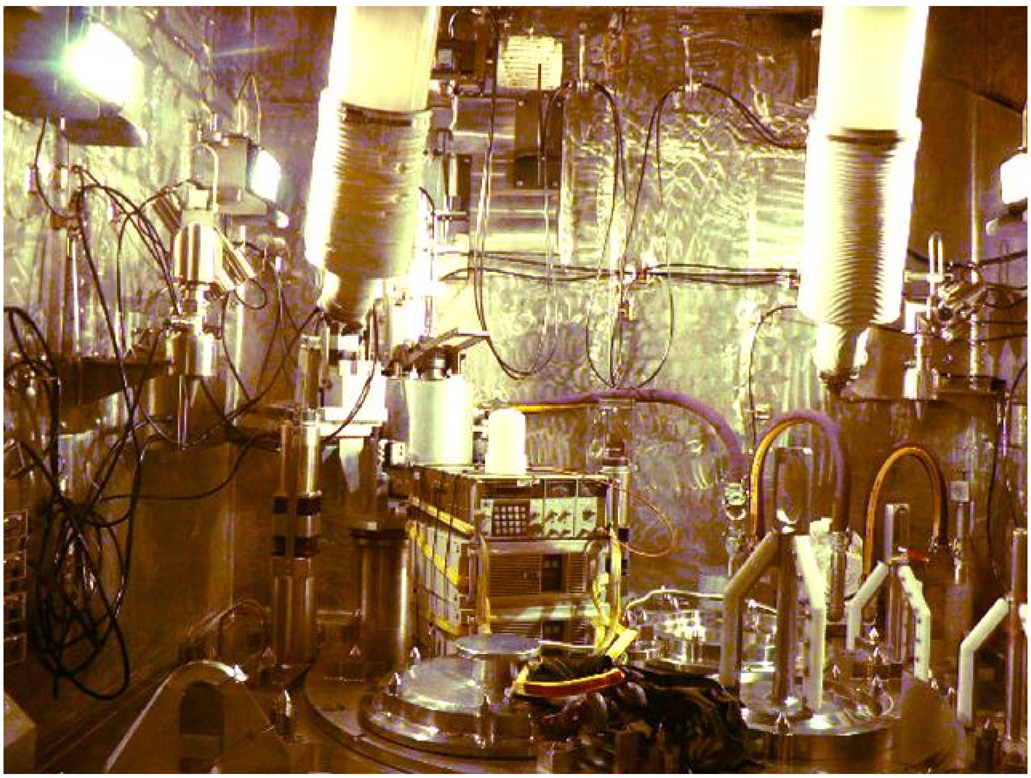

Figure 2: Typical Radiological Work Cell

There are many other applications in the NWC that can benefit from the use of wireless sensor technologies. Besides the transmission of signals through containment system boundaries, other applications involve sensor installations on unique component test equipment such as thermally controlled vibration tables, shock machines, and centrifuges where sealed rooms and test chambers, as well as moving parts, make wired sensors difficult to manage. Even the presence of slip rings for rotating equipment such as centrifuges only provides capacity for a limited number of signals and introduces a maintenance issue for the slip ring components. Other uses of wireless sensors arise in routine preventative maintenance diagnostic measurements performed on equipment including motors, fans, and bearing housings.

ASSET TRACKING

In addition to wireless sensor applications involving physical parameter measurements, wireless technologies have the potential to prove very beneficial in the tracking of various assets in the NWC. Radio Frequency Identification (RFID) is already being pursued for the tracking of nuclear material storage containers, exclusion of prohibited personally owned electronics from security areas, and tracking of accountable digital storage media. Other asset tracking applications involve the tracking of unique parts, components, and specialized tooling on the shop floor during a component assembly process. RFID could also be useful in the safe processing of nuclear material as an aid to ensuring that strict criticality mass limits are observed in the introduction of material into operating rooms and processing areas. The control and safe use of chemicals can also be improved through the use of RFID to ensure proper storage, handling, and correct identification prior to use.

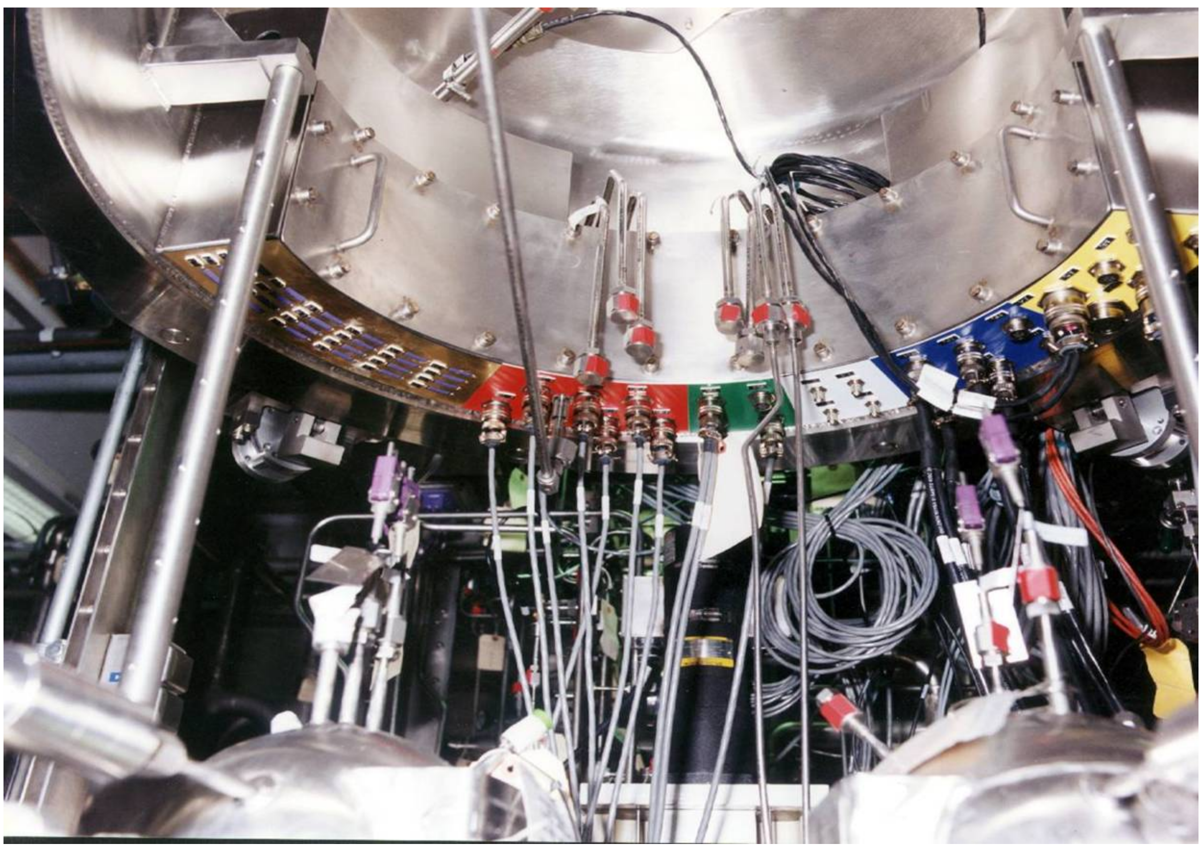

Figure 3: 800 Liter Bell Jar inside a Glove Box

There are, however, some familiar technical hurdles associated with RFID applications in the NWC and some unique challenges. Besides the familiar technical issues related to the performance of RFID on metal objects or containers, liquid-filled containers, and on or near personnel, one of the unique challenges that must be overcome in many asset tracking applications in the NWC is the RFID tag's susceptibility to ionizing radiation. In many nuclear material storage applications the expected cumulative lifetime dose could exceed 10^6 rad of gamma radiation. Radiation-hardened devices are needed to ensure low-maintenance operation over the expected storage lifetime of the material containers. Some tags that show promise in this area are passive devices utilizing radio frequency transmission with Surface Acoustic Wave (SAW) identification encoding. These devices are also suited for operation at temperatures of several hundreds of degrees C possibly up to 1000 °C and can survive radiation doses up to 5 x 10^6 rad[2]. Drawbacks to this type of tag include limited identification "bits", read-only, and difficulties in resolving multiple simultaneous tag responses. Some single-use/disposable components used in the pharmaceutical, bioprocess/biomedical, food and beverage, and medical industries have driven the development of a read/write RFID tag that can be subjected to sterilization process doses of gamma radiation up to 4.5 x 10^6 rad. Further development work is needed, however, by manufacturers to provide additional RFID options for the nuclear industry environment.

Figure 4: Thermally Controlled Vibration Table

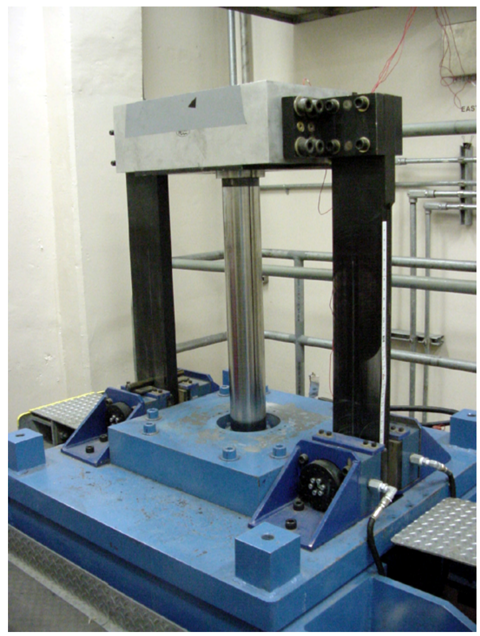

Figure 5: Shock Machine inside a Sealed Room

WIRELESS SENSOR REQUIREMENTS FOR THE NWC

With the many challenges associated with the harsh RF, physical, and regulatory environment present at the NWC sites, special consideration should be given to the type of wireless technologies deployed at these facilities. While each deployment will vary in complexity and adversity of conditions, wireless sensor network applications in the NWC should consider the following requirements and potential attributes:

Robustness: multi-path rejection capabilities, self-healing mesh network, spread spectrum modulation techniques (Direct Sequence Spread Spectrum (DSSS), Frequency Hopping Spread Spectrum (FHSS), Hybrid Spread Spectrum (HSS), Ultra-Wideband (UWB))
Latency: response times of less than 1 second
Security: encryption built-in to the physical layer, minimum required power level to avoid detection, directional antennas where appropriate, spread spectrum modulation techniques
Adherence to a National Standard: non-proprietary hardware, multiple vendors
Cost: low cost is not a major requirement considering the cost of cable and installation

Two developing spread spectrum modulation techniques that may have some potential advantages for NWC applications are Hybrid Spread Spectrum (HSS) and Ultra-Wideband (UWB). HSS combines some of the advantages of DSSS and FHSS. Benefits of a fast-hopping HSS (hops on the order of a bit rate) can include: superior multi-path rejection capabilities, improved data integrity and security, better low-probability-of-detection/low-probability-of-interception (LPD/LPI) properties, lower latency, superior jamming resistance, fast synchronization and higher user density, less mutual interference among users in a given area or frequency band, increased statistical signal diversity, superior near-far reception properties of FH, and lower overall peak power at any given frequency[3]. UWB uses very low power short duration transmissions to achieve very high data rates at short distances (500 Mbps at distances of 10 feet). The low power and short transmission durations provide improved LPD/LPI and decreases the likelihood of interfering with multiple users or other devices and equipment. UWB also provides high performance in multi-path environments and is resistant to narrowband jamming and interference. UWB also can be used for high-resolution localization providing sensor locations within 1 foot resolution.

Figure 6: Centrifuge Utilizing Slip Rings inside a Sealed Chamber

CURRENT DEPLOYMENT CASE STUDY

SRNL is currently pursuing the development and deployment of a wireless sensor network for use in a radioactive work cell. Cable penetrations into the work cell are at capacity pushing the cost of implementing a wired solution far above that of a wireless network. The desired deployment will provide a network of three temperature sensors and one oxygen level sensor. The measurement data will be transmitted through the work cell viewing window and will be displayed on a local computer display at the operator's work location. SRNL has acquired the assistance of Oak Ridge National Laboratory's (ORNL) Extreme Measurement Communications Center to provide analysis and design of the sensor network.

Background RF measurements were performed inside the work cell prior to the start of radioactive operations in the facility (See Figure 2 and Figure 7) to determine any potential sources of EMI and to assess the frequency transmission characteristics of the cell window. The technical requirements for the sensor network have been defined and conceptual design work has begun. Initial discussions with the reviewing and approving organizations are also underway to help identify any issues that may influence the conceptual design decisions.

Design challenges for this sensor network include gamma radiation fields on the order of 10^6 rad cumulative lifetime dose and the highly RF reflective environment present inside the work cell.

Figure 7: Background RF Survey Outside of Radiological Work Cell

CONCLUSION

NWC wireless technology applications offer unique challenges in the RF, physical, and regulatory environments. Special consideration and effort must be given to ensure successful wireless deployments in both the technical and approval aspects. Wireless technologies offer many advantages and high returns on investment or cost savings for many NWC applications including wireless sensor networks and asset tracking. Cost benefits may be realized in the design, work planning, installation, materials, maintenance, waste disposition, inspections, and approval aspects of existing facility modifications. Material savings alone can be very significant with some estimates of cabling for harsh nuclear environments reaching thousands of dollars per foot. The NWC must be prepared to adapt to a continuing trend in commercial products towards wireless connectivity. In the not-so-distant future, wired versions of many business products such as computer peripherals may not be readily available. The benefits of wireless technology for the NWC require a close look at the current state of the industry, the direction of new developmental work, and the formation of new industrial standards. Because of some of the unique challenges, however, additional work is needed to develop a robust wireless sensor platform that meets the unique operational and security requirements for many NWC deployments.

REFERENCES

[1] Curtis, R. A., (1999). Introduction to Ionizing Radiation. http://www.osha.gov/SLTC/radiationionizing/introtoionizing/ionizinghandout.html.

[2] Fachberger, R., Bruckner, G., Reindl, L., Hauser, R., White Paper - Tagging of Metallic Objects in Harsh Environments. http://www.airgatetech.com/AIRGATE/RFID-solutions/Project-SAW-Harsh-RFID.aspx.

[3] Moore, M. R., Smith, S. F. (2005). Improve Wireless Reliability with Fast-hopping Hybrid Spread Spectrum. http://www.isa.org/InTechTemplate.cfm?Section=Article_Index1&template=/ContentManagement/ContentDisplay.cfm&ContentID=49893.